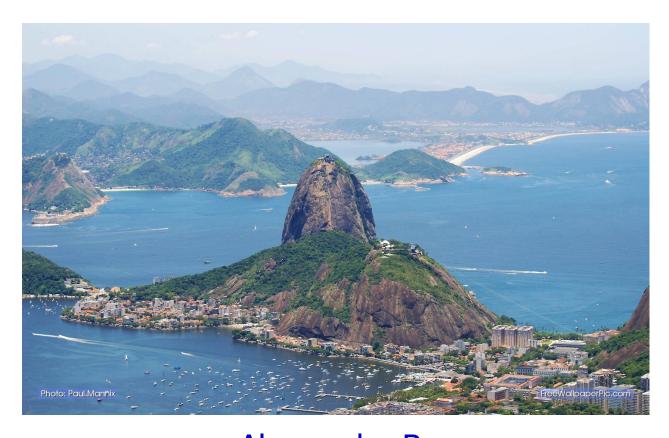
Pion Hadron Production in NA61





Alessandro Bravar (Université de Genève) for the NA61 Collaboration

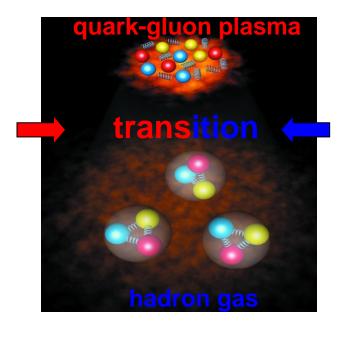


NA61 Physics Program

Physics of strongly interacting matter in heavy ion collisions

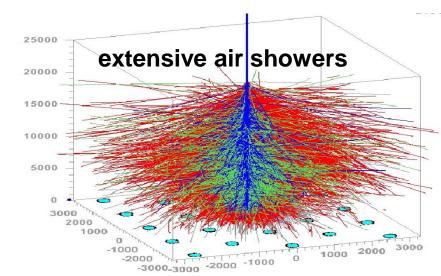
Search of the QCD critical point (AA and pA collisions)

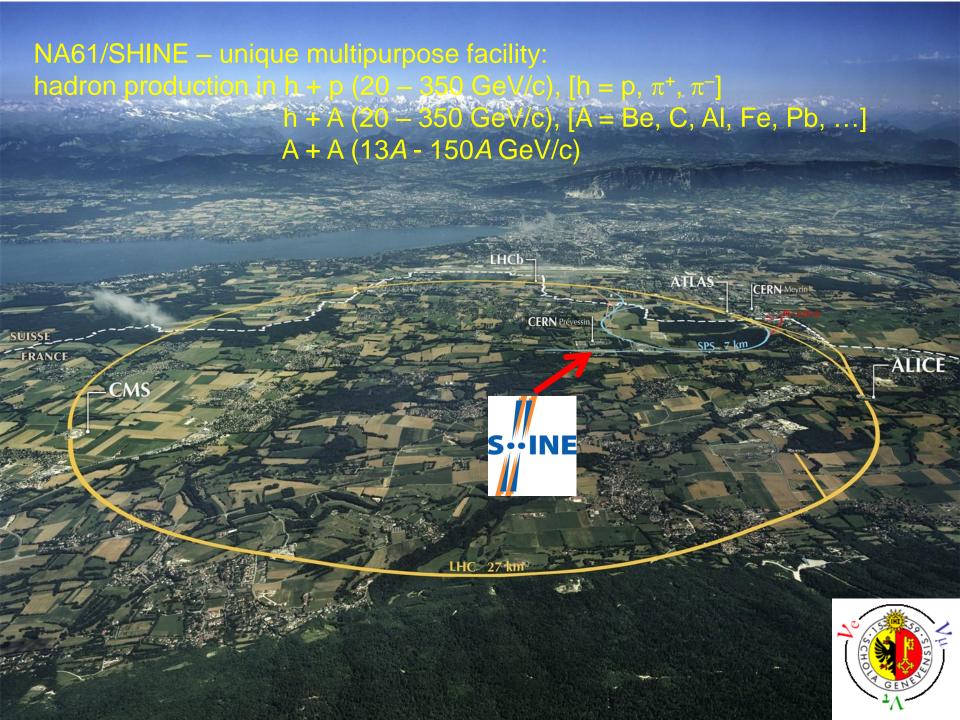


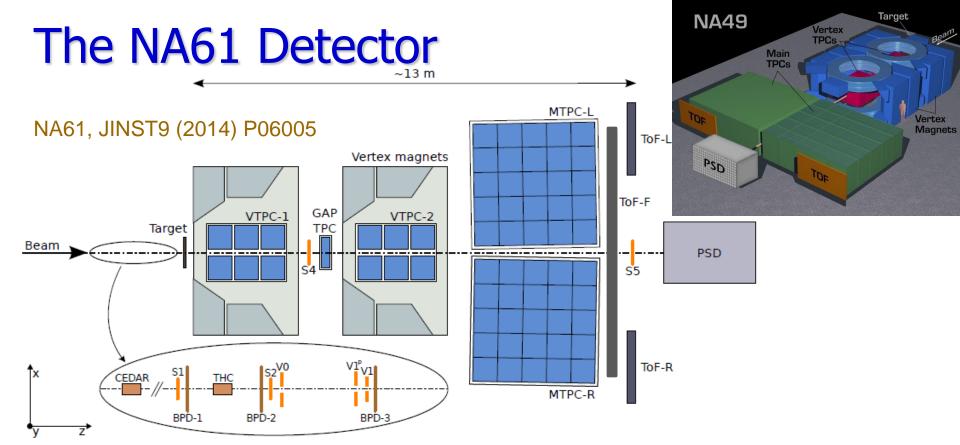


Hadron production measurements on the T2K target (p+C) to characterize the T2K neutrino beam soon also measurements for NuMI

Measurement of hadron production in p+C interactions needed for the description of cosmic-ray air showers (Pierre Auger Observatory and KASCADE experiments)



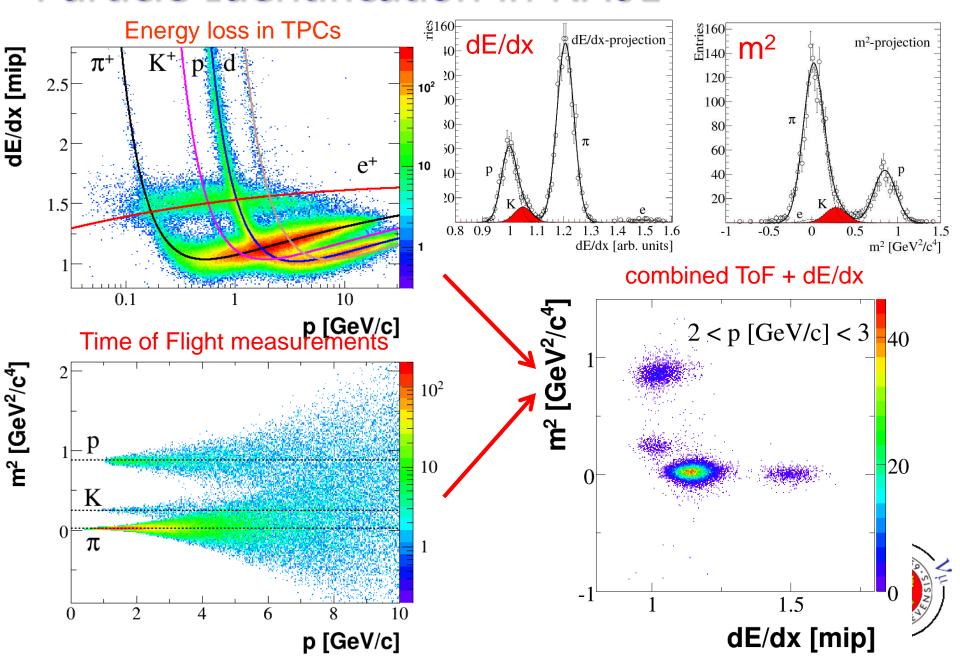


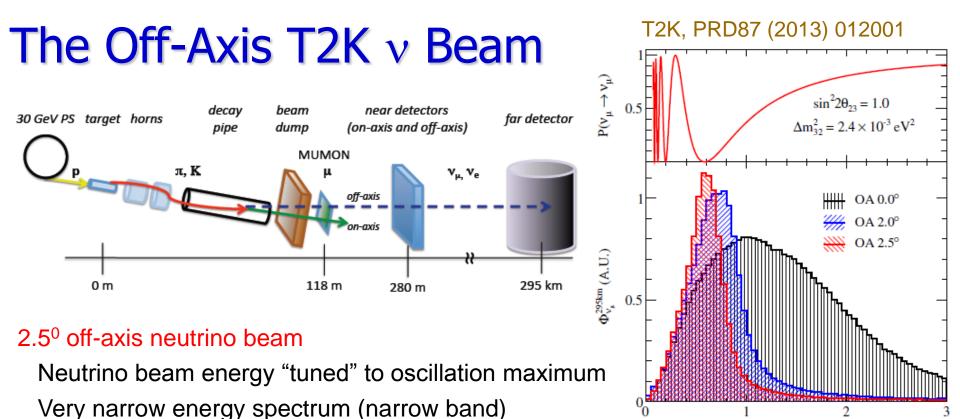


large acceptance spectrometer for charged particles

- 4 large volume TPCs as main tracking devices
- 2 dipole magnets with bending power of max 9 Tm over 7 m length (T2K runs: ∫Bdl ~ 1.14 Tm) high momentum resolution
- good particle identification: $\sigma(\text{ToF-L/R}) \approx 100 \text{ ps}$, $\sigma(\text{dE/dx})/<\text{dE/dx}>\approx 0.04$, $\sigma(m_{\text{inv}}) \approx 5 \text{ MeV}$ new ToF-F to entirely cover T2K acceptance ($\sigma(\text{ToF-F}) \approx 100 \text{ ps}$, $1 , <math>\theta < 250 \text{ mrad}$) several additional upgrades are under way

Particle Identification in NA61





Neutrino source created by interactions of 30 GeV protons on a 90 cm long graphite rod

Neutrino beam predictions rely on modeling the proton interactions and hadron production in the target

Horn focusing cancels partially the p_T dependence of the parent pion

Neutrino beam energy almost independent of parent pion energy

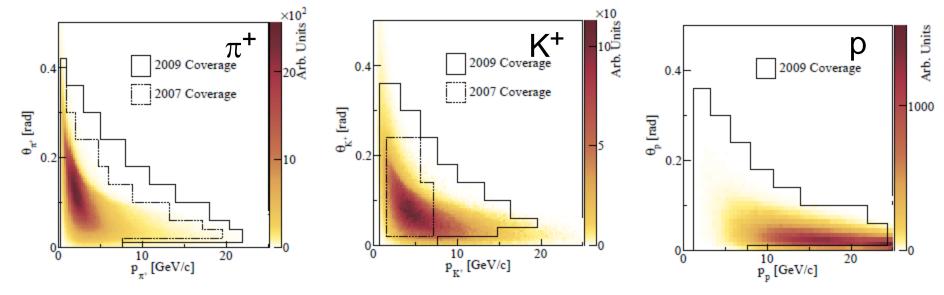
Precise hadron production measurements allow to reduce uncertainties on neutrino flux prediction



 E_{ν} (GeV)

Required Acceptance for v Flux Calculations

T2K v parent hadron phase space 30 GeV proton beam on the 90 cm long T2K graphite target



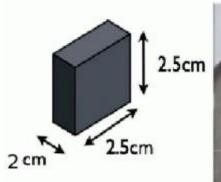
note: this is not a cross section it shows the distributions of π , K, and contributing to the ν flux at SK

need to cover this kinematical region and identify the outgoing hadrons K component important for v_e appearance signal

requires detector with large acceptance
with excellent particle ID capabilities
with high rate capabilities to accumulate sufficient statistics

The NA61 Targets

2 different graphite (carbon) targets







Thin Carbon Target

- length=2 cm, cross section 2.5 x 2.5 cm²
- $\rho = 1.84 \text{ g/cm}^3$
- \sim 0.04 λ_{int}

T2K replica Target

- length = 90 cm, $\emptyset = 2.6 \text{ cm}$
- $\rho = 1.83 \text{ g/cm}^3$
- \sim 1.9 λ_{int}

2007 pilot run

2009 run

2010 run

Thin target:

~660k triggers

~6 M triggers

(⇒ 200 k π + tracks in T2K acc.)

Replica target: ~230k triggers

~2 M triggers ~10 M triggers



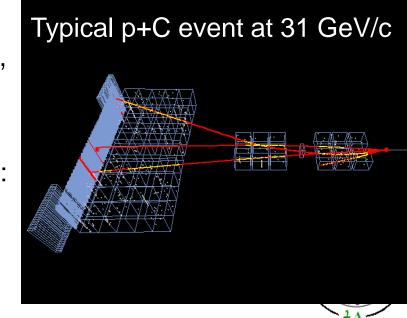
Analysis Methods

Different analysis procedures adopted depending on the kinematical region covered:

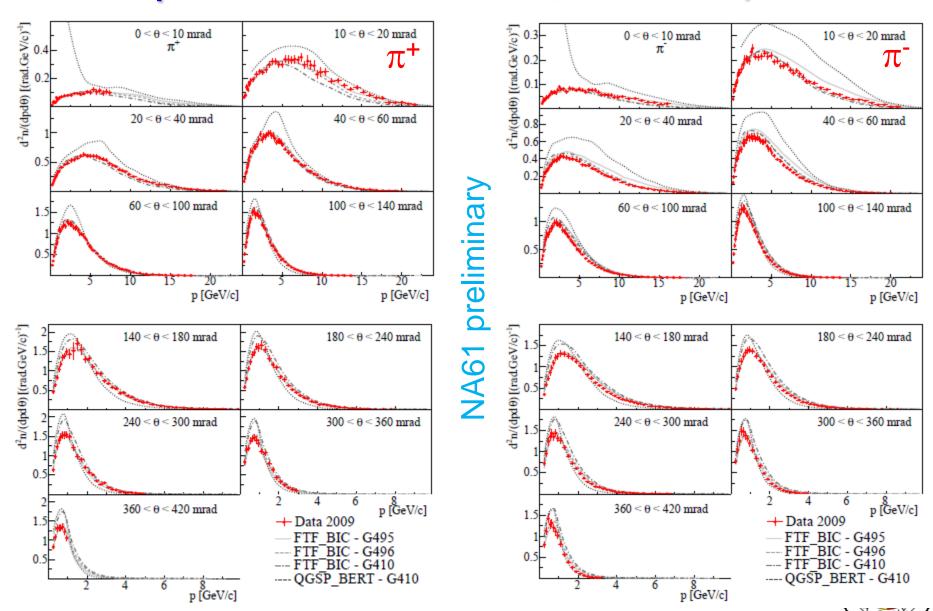
- 1) negative hadrons: at this beam energy (31 GeV/c) most (> 90%) negative hadrons are π^- with small K⁻ contamination (< 5%) pure tracking with no PID, large acceptance, global MC correction
- 2) p < 1 GeV/c PID based on dE/dx only (below cross-over region in dE/dx)
- 3) p > 0.8 GeV/c PID combined ToF dE/dx analysis

(π / K / p separation)
particles must reach the ToF, reduced acc.;
factorize all corrections (i.e. acc., recon. eff., decays, etc.), some corrections estimated directly from data, rely less on MC

raw measured particle spectra corrected for:
geometrical acceptance
reconstruction efficiency
non-pion contributions
weak decays (feed-down)
trigger bias

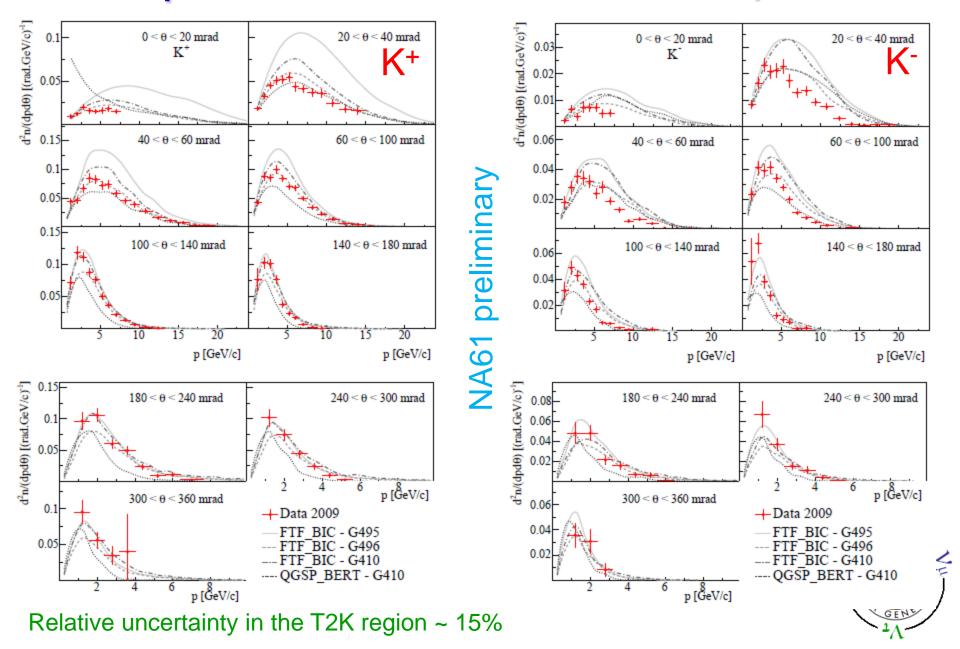


NA61 p + C $\rightarrow \pi^{+/-}$ + X @ 31 GeV/c

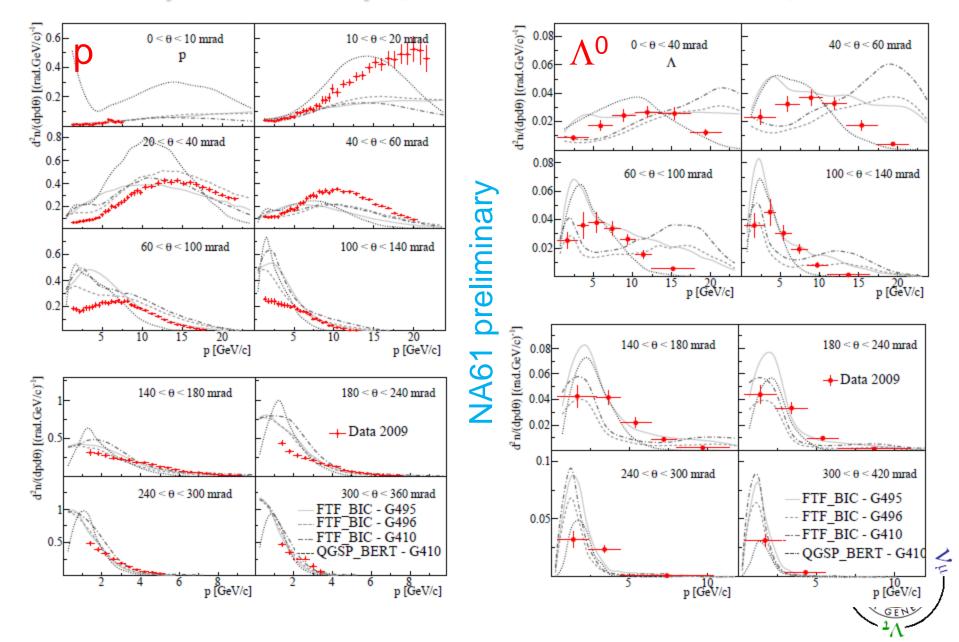


Relative uncertainty in the T2K region ~ 4%

NA61 p + C \rightarrow K^{+/-} + X @ 31 GeV/c

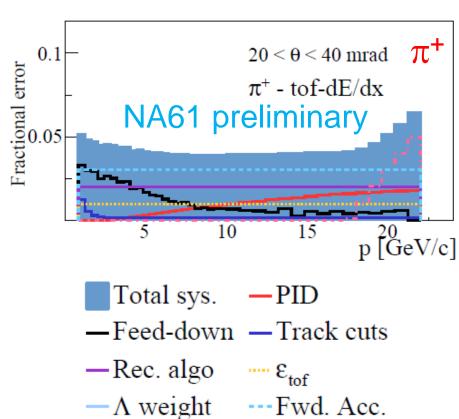


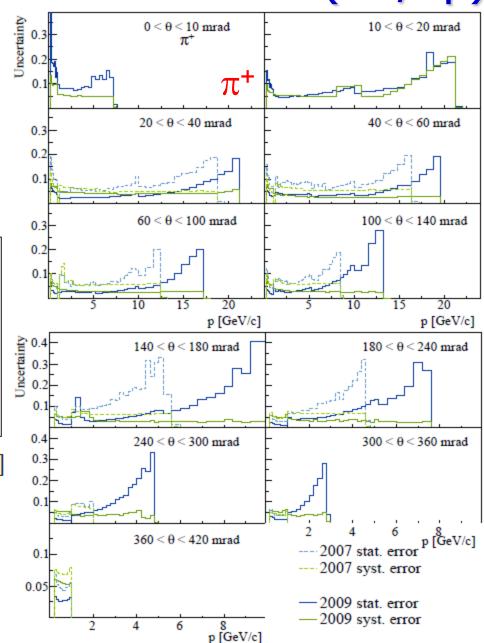
NA61 p + C \rightarrow p / Λ + X @ 31 GeV/c



NA61 p + C $\rightarrow \pi^+$ + X Uncertainties (dN/dp)

Compared to 2007 data:
statistical uncertainty
improved by ~3
systematical uncertainty
reduced by ~ 2





Already Published NA61 Data

Measurements of cross sections and charged pion spectra in proton-carbon interactions at 31 GeV/c

Phys. Rev. C 84, 034604 (2011)

Measurement of production properties of positively charged kaons in proton-carbon interactions at 31 GeV/c

Phys. Rev. C 85, 035210 (2012)

Pion emission from the T2K replica target: Method, results and application Nucl. Inst. and Meth. A 701 (2013) 99–114

Measurement of negatively charged pion spectra in inelastic p+p interactions at $p_{\text{lab}} = 20$, 31, 40, 80 and 158 GeV/c Eur. Phys. J. C (2014) 74:2794

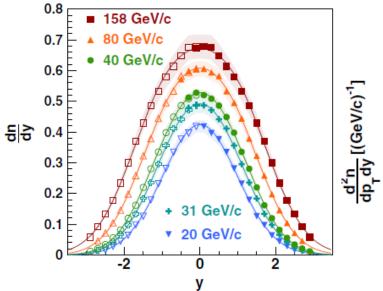
Measurements of production properties of K^0_S mesons and hyperons in proton-carbon interactions at 31 GeV/c

Phys. Rev. C 85, 025205 (2014)

π^- Spectra in p + p $\rightarrow \pi^-$ + X Energy Scan

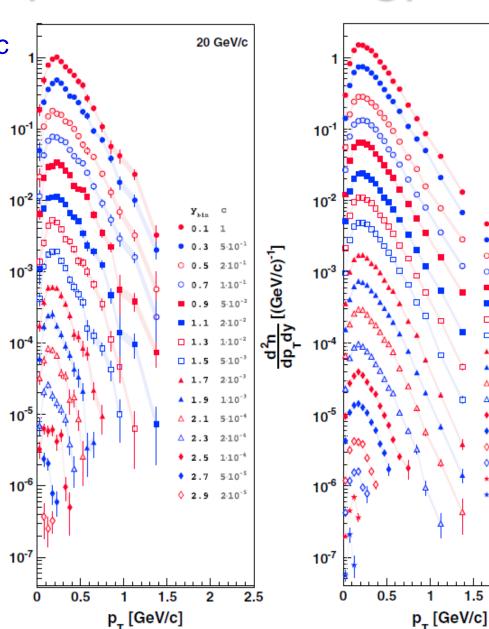
 $p_{lab} = 20, 30, 40, 80, 158 \text{ GeV/c}$





p + p symmetric in rapidity (and x_F) 10-6 negative $y(x_F)$ by reflection

$$(y = 0 \rightarrow x_F = 0)$$



158 GeV/c

1.3 1·10⁻²

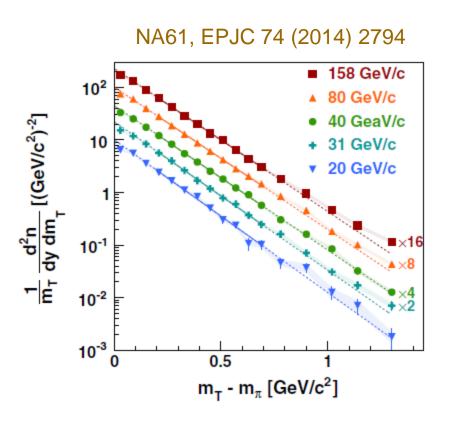
* 3.3 5·10⁻⁶

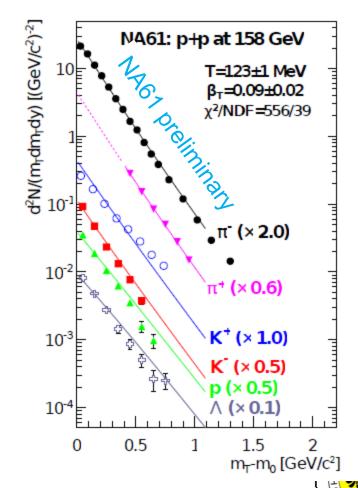
★ 3.5 2·10⁻⁶

Transverse Mass Spectra at Mid-Rapidity

 $p + p \rightarrow h + X @ 158 GeV/c$

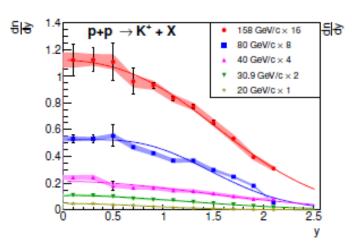
transverse mass: $m_T^2 = m_0^2 + p_T^2$ mid-rapidity: y = 0 ($x_F = 0$)



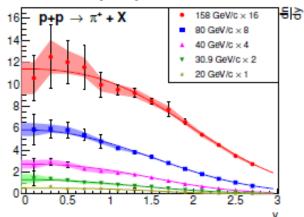


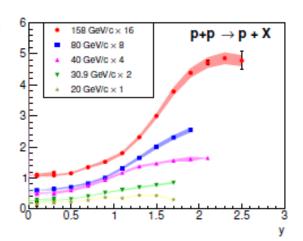
Transverse mass spectra are approximately exponential in p + p interactions

$p + p \rightarrow h + X : dn/dy (Energy Scan)$



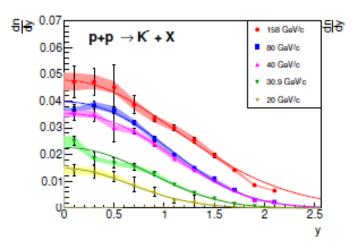
K, π , p: positive

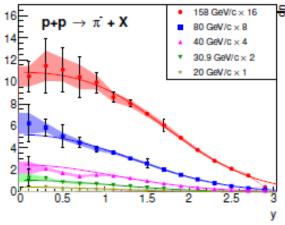


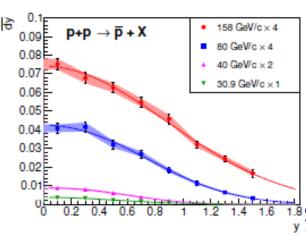


NA61 preliminary

K, π , p: negative



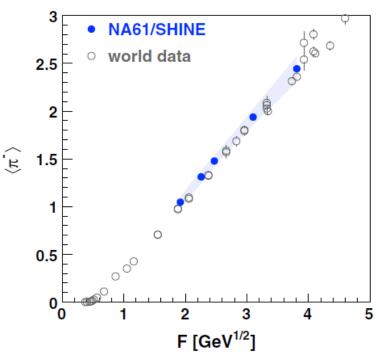






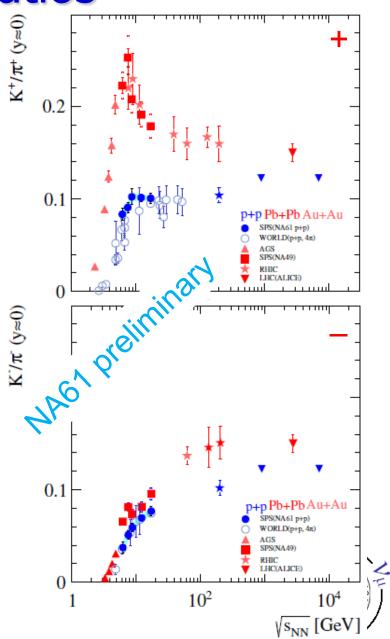
π Multiplicities and K/π Ratios



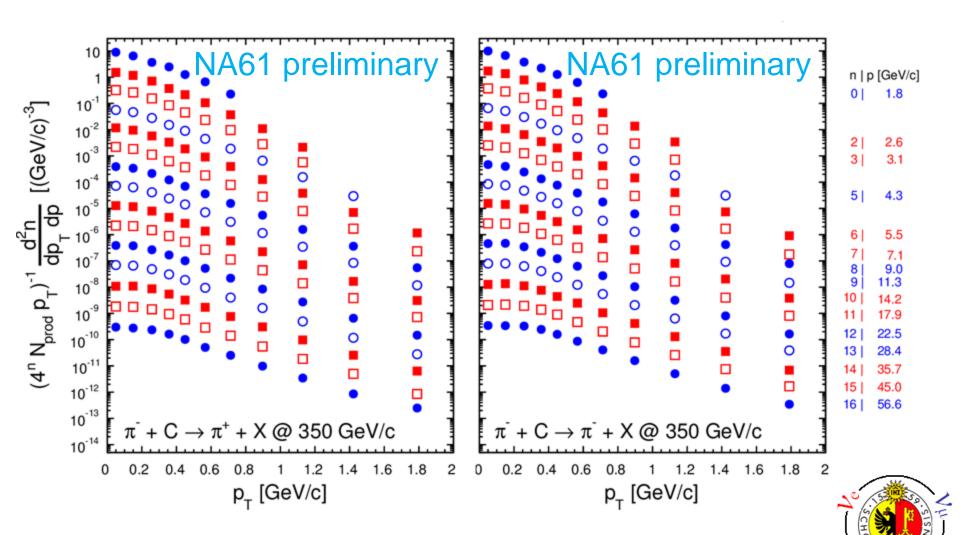


Fermi energy

$$F \equiv \left[\frac{(\sqrt{s_{\rm NN}} - 2m_{\rm N})^3}{\sqrt{s_{\rm NN}}} \right]^{1/4}$$



Charged π spectra in π^- + C Interactions



Some Observations

p + p and p + C data is unexpectedly interesting

None of the hadroproduction models describes satisfactorily ensemble of the $p + C \rightarrow h + X$ hadroproduction data

Models do not describe well the NA61/SHINE data on p + p interactions

High precision NA61/SHINE data presents a challenge for models and allow for significant improvement of models

Even in p + p the energy dependence of the K⁺/ π ⁺ ratio exhibits rapid changes in the SPS energy range

Soon p + C data at different energies (60 GeV/c, 120 GeV/c) Also Be, Al, Pb

Soon comparison of p + p and p + A hadroproduction data

- → A dependence
- → energy dependence



Neutrino Source Production

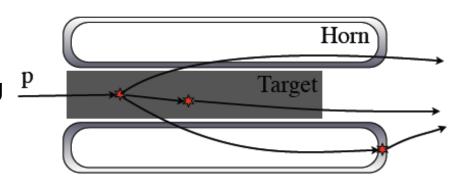
direct contribution:

secondary hadrons exit the target and decay into ν

We see only particles coming out of the target We do not see what happens inside the target

target contribution:

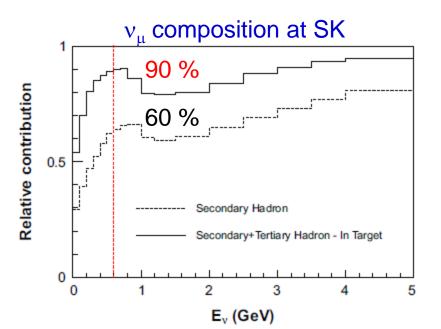
secondary and tertiary hadrons exiting the target and decaying into v

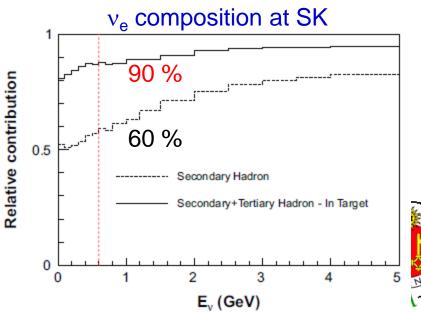


non-target contribution:

re-interaction in the target surrounding material

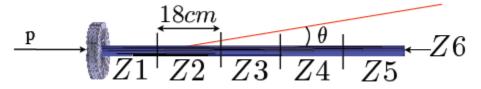
NA61, NIM A701 (2013) 99





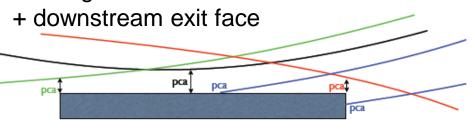
π^+ Hadroproduction on T2K Replica Target

Hadron multiplicities are measured at the target surface in bins of $\{p, \theta, z\}$



Tracks are extrapolated backwards to the target surface (point of closest approach)

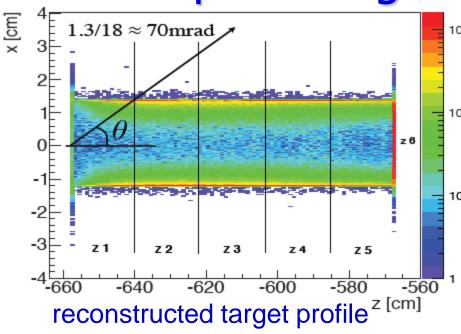
the target is sliced in 5 bins in z

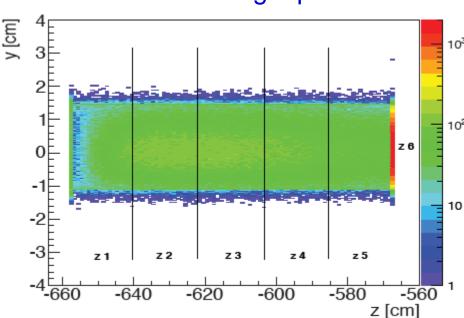


No interaction vertex reconstruction can study also as a function of r

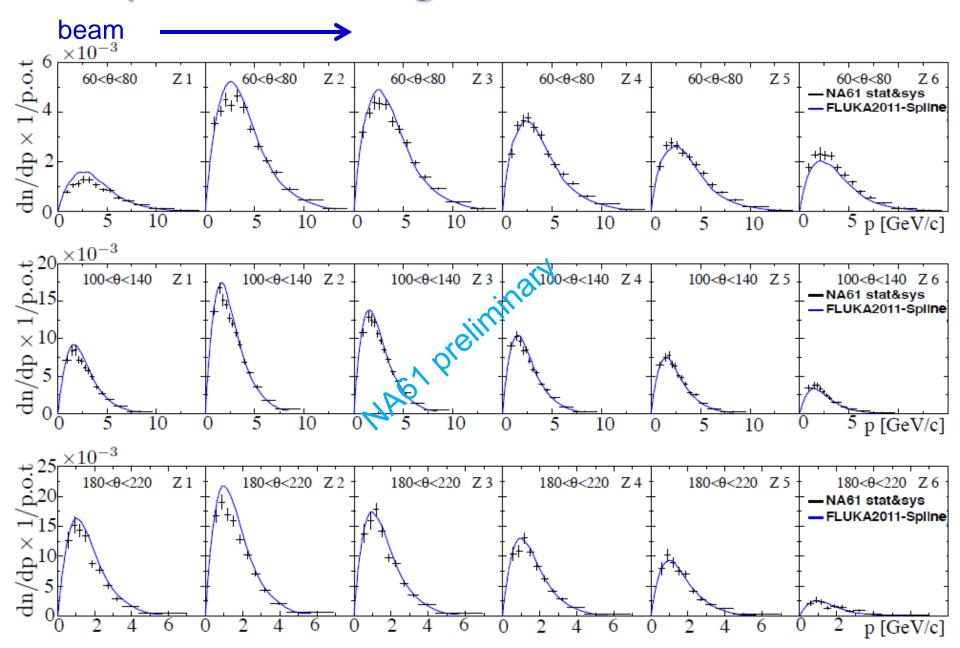
Statistical precision ~5%

Systematic error ~5%





π^+ Spectra on Target Surface



NA61 4 NuMI (USNA61)

Perform hadron production measurements to characterize the NuMI v beam

Target

using the NA61 detector at CERN mainly US groups

Data taking to start this fall

tentative run plan

proton+pion event totals Incident proton/pion beam momentum Target 120 GeV/c 60 GeV/c 30 GeV/c NuMI (spare) replica (future) LBNE replica (future) thin graphite ($< 0.05\lambda_I$) 3M3M (T2K data) thin aluminum ($< 0.05\lambda_I$) 3M (future) thin steel ($< 0.05\lambda_I$) (future) (future) (future) thin beryllium ($< 0.05\lambda_I$) 3M3M (future)



MTPC-L

ToF-L

neutrons

PSD

Upgrades:

Vertex magnets

VTPC-2

GAP

VTPC-1

add forward tracking forward calorimetry (neutrons) new DAQ based on the DRS better trigger

Conclusions

NA61 is providing valuable data to constrain the T2K neutrino flux

NA61 initial goals for T2K: 5% error on absolute neutrino fluxes 3% error on the far-to-near ratio

Hadro production measurements require

large acceptance detectors with PID over whole kinematical range large statistics different targets to study various particle production effects

Hadroproduction of $\pi^{+/-}$, $K^{+/-}$, p, K^0_s , Λ in p + p and p + C interactions at different energies Soon also on Be, AI, and Pb targets

- \rightarrow comparison of p + p and p + A data
- → A dependence

Hadroproduction measurements also with π beams

High precision NA61/SHINE data presents a challenge for hadroproduction models

NA61 to continue with hadron production measurements for NuMI, starting this fall